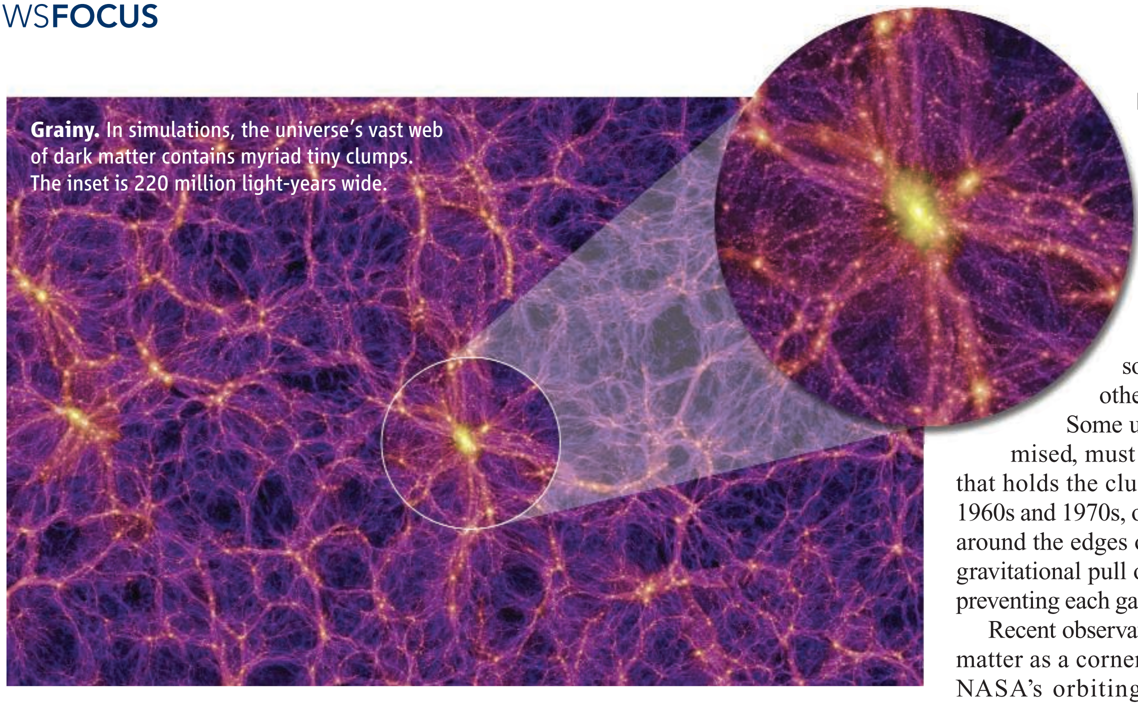

Grainy. In simulations, the universe's vast web of dark matter contains myriad tiny clumps. The inset is 220 million light-years wide.

ASTRONOMY

Where Are the Invisible Galaxies?

Cosmology predicts an abundance of small galaxies made entirely of dark matter, but astronomers haven't found any yet

CARDIFF, UNITED KINGDOM—Whorls of innumerable stars, galaxies shine across the boundless darkness, their ancient light recording the nature and history of the universe. So entwined are the notions of star, light, and galaxy that one might expect astronomers and astrophysicists to snicker at the seemingly absurd idea of a dark galaxy, one devoid of light and stars. But many say that such things must abound, and 92 researchers gathered here recently to hash out both how to detect them and whether the fact that they haven't seen any poses a serious challenge to some fundamental theories.*

The questions have been foisted upon astronomers by cosmologists and their understanding of how the universe blossomed from the big bang. According to the increasingly refined theory, 85% of the matter in the universe is not the ordinary matter that makes up stars and galaxies, planets and people. Rather, it is elusive dark matter that so far has revealed itself only through its gravity. As the infant universe grew, the dark matter condensed into enormous filaments and clumps, or "halos." These weighty objects pulled in hydrogen gas, which formed stars and galaxies.

But there's a catch: Simulations show that dark matter should have formed myriad clumps between 1/1000 and 1/1,000,000 as massive as the Milky Way galaxy. At first blush, these small halos should have accumulated gas and lit up as small "dwarf galaxies," thousands of which should whiz around the Milky Way. So far, astronomers have spotted only a few dozen nearby—although they're finding more. Various factors may have kept the small halos dark. But then space ought to teem with tiny dark galaxies, and astronomers have yet to find any. "If they don't exist, then it's an enormous problem for astrophysics," says Jonathan Davies, an astronomer at Cardiff University in the U.K.

But other astronomers say the so-called missing satellites problem is an artifact of the simulations, which do not account for how individual galaxies form. Instead, the simulations track the evolution of dark matter alone and then "paint" the galaxies onto filaments and clumps. "It could simply be that the assumptions that go into the [computer] code are wrong, and that if you do dark-matter-only simulations you get the wrong answers," says Albert Bosma of the Marseille Observatory in France.

Complicating matters, researchers do not agree on precisely what a dark galaxy is. Polite disagreement escalates to acrimony when discussion turns to the question of whether one group has actually spotted one.

Dark galaxies galore

Dark matter was dreamt up 70 years ago. In 1933, Fritz Zwicky, an astronomer at the California Institute of Technology in Pasadena, noted that some galaxies in the Coma cluster were moving so fast that the gravity of the others could not rein them in. Some unseen dark matter, he surmised, must provide the extra gravity that holds the cluster together. Then in the 1960s and 1970s, others found that stars whiz around the edges of galaxies so fast that the gravitational pull of dark matter seems to be preventing each galaxy from flying apart.

Recent observations have established dark matter as a cornerstone of cosmology, too. NASA's orbiting Wilkinson Microwave Anisotropy Probe (WMAP) has mapped in exquisite detail the afterglow of the big bang, the cosmic microwave background radiation. The temperature of the microwaves varies slightly across the sky, and the pattern reveals much about how the universe evolved. In 2003, WMAP researchers found they could account for the pattern if the universe contains precisely 4% ordinary matter, 23% dark matter, and 73% mysterious space-stretching dark energy.

But even before then, theorists knew dark matter caused problems on smaller scales. The stuff acts like a weighty, frictionless fluid, which is easy to model. Since the 1990s, simulations have shown that it should form a multitude of small clumps. "The simulations predict that there should be thousands of dark galaxies in the halo of the Milky Way," says Carlos Frenk, a cosmologist at Durham University in the U.K. and a co-author of the state-of-the-art Millennium Simulation. "If they are not there, then the fundamentals of cold dark matter are wrong."

Discounting that possibility, theorists have tried to explain why small dark-matter halos might not evolve into visible galaxies. Ultraviolet light from the first stars should have ionized and heated the hydrogen in small clumps, preventing it from condensing into stars. Alternatively, small halos may have formed massive stars that quickly blew up in supernova explosions, blasting the remaining hydrogen into space and leaving the clumps barren. Together, the mechanisms resolve the discrepancy between the number of predicted and observed dwarf galaxies, Frenk says.

That explanation strikes some as a just-so story. Erwin de Blok of the University of Cape Town, South Africa, distrusts the simulations that predict large numbers of small halos.

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* International Astronomical Union Symposium 244: Dark Galaxies and Lost Baryons, 25–29 June.

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Using the Very Large Array of radio telescopes in New Mexico, he and colleagues measured the speeds of stars in 35 galaxies and found that the simulations do not precisely reproduce the velocity distributions—the very things that dark matter was originally supposed to explain. That discrepancy suggests dark-matter-only simulations are reliable only on scales larger than galaxies, de Blok says. “Once you go to small scales, then you have to take into account the physics” of ordinary matter, he says.

Spotting the invisible

Ultimately, observations will reveal whether dark galaxies abound. Much effort has focused on radio astronomy. Dark halos might collect some atomic hydrogen, which emits radio waves of a distinct wavelength, 21 centimeters. So a dark galaxy should appear as a starless source of such hydrogen-one, or HI, radiation. Astronomers have used the 64-meter dish at the Parkes Observatory in Australia to search for HI sources in the HI Parkes All-Sky Survey (HIPASS). They spotted 4315, and simulations suggested that 86 of them should be dark galaxies.

But all but a couple of the sources are associated with galaxies, the team reported 2 years ago. “That’s a very big surprise,” says Michael Disney of Cardiff University, who worked on HIPASS. However, dark and ordinary galaxies might often line up in the sky by chance. “That leaves room for dark galaxies even though it appears that there aren’t any,” Disney says. More sensitive surveys called ALFALFA and AGES are under way at the Arecibo Observatory in Puerto Rico.

Others hope to track down dark galaxies by their gravity. Gravity from one galaxy can bend the light of another behind it so that the farther galaxy appears as a ring around the nearer one, an effect known as strong lensing. The details of the ring depend on the distribution of matter in the nearer galaxy and might reveal small dark galaxies orbiting it, says Leon Koopmans of the University of Groningen in the Netherlands. Since 2003, he and colleagues have spotted more than three dozen rings in data from the Sloan Digital Sky Survey, which uses a 2.5-meter telescope at Apache Point, New Mexico, and from the Hubble Space Telescope. They hope to finish the analysis within 2 years.

Some researchers aim to spot dark galaxies crashing into ordinary ones. Galaxies collide and tear one another in so-called tidal interactions, and about 8% of galaxies exhibit such damage. If dark galaxies are as common as ordinary ones, then the same fraction of seemingly isolated galaxies should have collided with invisible dark galaxies, reasons Igor Karachentsev of the Special Astrophysical Observatory of the Russian Academy of Sciences in the Republic of Karachay-Cherkessia. But analyzing about 1500 isolated galaxies from three catalogs, he found that only nine, or 0.6%, showed signs of a collision, suggesting that dark galaxies are rare.

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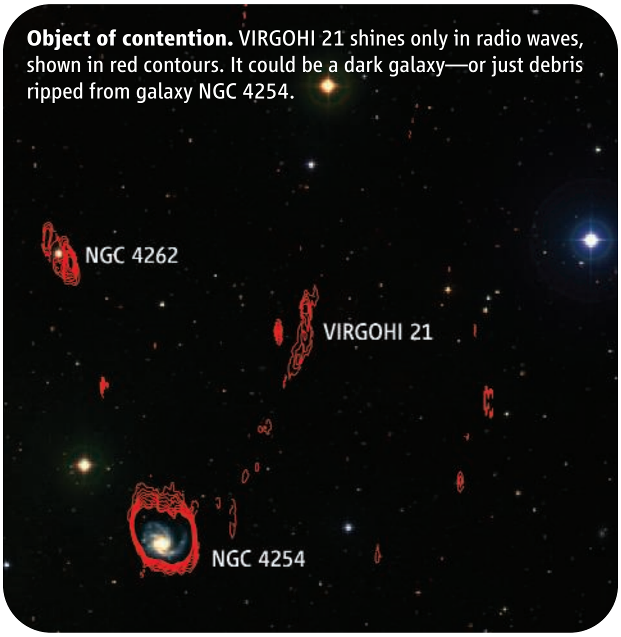

Object of contention. VIRGOHI 21 shines only in radio waves, shown in red contours. It could be a dark galaxy—or just debris ripped from galaxy NGC 4254.

Even as astronomers hunt for dark galaxies, they disagree about exactly what they’re looking for. Some, such as Cardiff’s Davies, say that a dark galaxy is anything dark with the mass of a galaxy. Others say that catholic definition could include simple clouds of ordinary gas. Edward Taylor of Leiden University in the Netherlands says a dark galaxy is an ancient dark halo that collected hydrogen but never formed stars. That more specific definition appeals to many, but it may not be very helpful, either. Even Taylor says he’s “fundamentally convinced that such objects do not exist.” His theoretical work shows that any dark halo massive enough to collect hydrogen will eventually produce stars, too.

The murky case of VIRGOHI 21

The debate over the definition of a dark galaxy pales in comparison to the dispute over whether one has been spotted. In 2001, Davies, Disney, and colleagues used the Jodrell Bank radio telescope in Macclesfield, U.K., to detect an HI source that shone no visible light in the Virgo cluster about 50 million light-years away. They dubbed it VIRGOHI 21, and in 2005, they argued that its spectrum suggests it is a rotating dark galaxy that has snatched hydrogen from a nearby galaxy called NGC 4254. Images taken more recently with the Westerbork Synthesis Radio Telescope near Hooghalen, the Netherlands, bolster their claim, they say.

But others doubt that interpretation, and only recently has a paper laying it out been accepted for publication in *The Astrophysical Journal*. Researchers working with the massive 305-meter radio dish at Arecibo have studied VIRGOHI 21 and believe it is part of a much longer stream of material ripped out of NGC 4254 by an ordinary galaxy passing at high speed. “What you’re looking at is most likely the result of a tidal encounter,” says Riccardo Giovanelli of Cornell University. Pierre-Alain Duc of the French Atomic Energy Commission in Saclay has used a computer to show he can model the collision.

Davies says he claims only that VIRGOHI 21 *could* be a dark galaxy. Disney goes further. “If you try to model it as tidal debris, you can’t,” he says. “When you look at the simulations in detail, they do not work.” Such pronouncements elicit grumbles. “This is not true and it’s not fair,” says Brent Tully, an astronomer at the University of Hawaii, Manoa. “There are referees [for the paper] in this room—I was a referee—and I’m sorry, but you didn’t convince me.”

Regardless of whether VIRGOHI 21 is a dark galaxy, closer to home the missing satellites problem appears slightly less alarming than it did a few years ago. Astronomers keep spotting new dwarf galaxies on the periphery of the Milky Way, narrowing the gap between the number predicted and the number observed. The Sloan survey, which covers a fifth of the sky, has identified 51, reports Eva Grebel of the University of Heidelberg in Germany. Using Sloan data and the Keck II telescope in Mauna Kea, Hawaii, Marla Geha of the Herzberg Institute of Astrophysics in Victoria, Canada, and a colleague found eight more. “Adding these in, the problem is at least eased,” Geha says.

Eased but not solved. “More and more of these objects will be found,” Grebel predicts, but “probably not enough to solve the missing satellites problem.” She estimates that astronomers still see only 1/5 as many small galaxies as the dark-matter simulations predict.

That suggests there are lots of truly dark galaxies out there. Astronomers will surely continue to look for them. After all, a dark galaxy would shine new light on the universe—and glory upon its discoverer. **–ADRIAN CHO**

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